INVESTIGATION OF TOUGHNESS OF ALUMINUM MAGNESIUM WELDMENTS

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C.M. Adams, Jr.

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Division of Sponsored Research
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Contract No. DA-19-020-507-ORD-4602

Boston Procurement District
OMS No. 5026.11.84300.51
DA Project No. 1-H-0-24401-A-111-01

Frankford Arsenal
Philadelphia 37, Pennsylvania

The findings in this report are not to be construed as an official Department of the Army position.

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I. Introduction

By reason of their plasticity and strength level in the welded condition, aluminum alloys containing between 4.0 and 5.5 per cent magnesium as the principal alloy element, are gaining wide acceptance in high strength light weight fabricated structures. The alloys are strengthened partly by solid solution hardening and partly by cold work, and, in the wrought condition, exhibit tensile and yield strengths and elongations above 40,000 psi, 30,000 psi, and 10%, respectively. In the welded condition, part of the strengthening induced by cold work is lost, but even so, the strength level of 5,000 series alloy weldments compares favorably with the only weldable heat treatable aluminum alloy of any importance, 6061, and the energy absorbing capability or toughness is far superior to that of any heat treatable aluminum alloy in the welded condition. It is this combination of moderate strength with high energy absorbing capability which is of interest in addressing the aluminum-magnesium alloys to fabrication of light weight armor. Secondly, but still of real significance, the aluminum-magnesium alloys offer atmospheric corrosion resistance quite superior to that of other high strength aluminum alloys.

A survey study of the strength and plastic properties of welded aluminum-magnesium alloys constituted the principal effort in an initial investigation[1,2], which was principally concerned with the influence of such

welding variables as arc energy input and filler metal composition on the overall strength and energy absorbing capabilities of various plate materials welded at different levels of initial cold work. These studies were conducted at low rates of strain (i.e. the order of 0.025 min^{-1}), and the principal findings were: (1) The variables of welding and initial plate condition generally exhibited a profound influence on the strain distributions observed in welds subjected to transverse tension, but the overall strength and toughness properties, at these low strain rates, were surprisingly insensitive to process variables. (2) The plastic properties of material in the weld zone, the heat affected zone, and the unaffected base material frequently appeared in sharp contrast to one another, as reflected in markedly non-uniform strain distributions. (3) Joint geometries and welding procedures were developed which reliably deposit welds substantially free of porosity, but at the same time it was found, in these alloys, gas porosity, even when severe, exerted little influence on transverse tensile properties.

In spite of the fact that the integrated strength and plasticity characteristics of 5,000 series weldments were found insensitive to process variables, there was fundamental interest in the properties of individual regions in the weld metal, and the heat affected zone, and the influence strain rate might have on these properties. Of particular interest were variables influencing weld metal properties, since in most cases

it was the weld metal which was strength limiting to the structure, and the observation of plastic behavior at impact strain rates, at various locations in the weld and the heat affected zone, were considered vital in view of the contemplated use of this material in light weight armor. Accordingly, a more detailed study of metallurgical responses and reactions in welding was initiated.

II. Experimental Program and Procedures

A. Materials

Previous work had clearly shown that the highest integrated strength and toughness were associated with matching or over-matching the filler to the base material with respect to magnesium content, i.e. that the weld metal should contain as much or more magnesium than the base material in order to prevent excessive strain concentration in the weld zone under transverse testing, and thereby promote strength and toughness. For this reason, all of the work reported herein concerns filler compositions 5183 and 5356. The 1/2 inch thick base materials were 5086, 5083, 5356, and 5456. The nominal and the exact compositions of the plate and wire materials are presented in Table I.

Detailed heat affected zone studies at low as well as impact rates of strain were made in 5086-H112, 5083-F, and 5356-H321, using miniature tensile and tensile impact test specimens. Small specimens were also used to observe properties in weld fusion zones in the transverse and

longitudinal directions using 5183 and 5356 filler on 5083 and 5456 base material (all four combinations).

B. Welding Procedure

The modified double - "U" preparation described in earlier reports was used throughout this study, and all welds were deposited with two passes, one from each side, using an inert gas shielded consumable electrode apparatus powered by constant potential transformer rectifier, adjusted to give the conditions shown below in Table II.

TABLE II

Welding Conditions

Shielding Gas	Helium
Gas flow rate	80 cfh
Carriage speed	15 ipm
Gun angle (from vertical)	15 ^{o}
Gun height	1/4- 3/8 in.
Open circuit voltage	34 v.
Welding voltage	31-32 v.
Amperage	260-270 a.

C. Mechanical Tests

The specimen used for both impact and strain rate tensile testing was a standard 0.1 inch diameter 0.75 inch gage length bar shown in Figure 1. Low strain rate tests were performed on an Instron machine, and tensile impact data were obtained using a drop

weight impact machine equipped with a load cell and oscilloscope, on which load-time curves were recorded photographically. With auxiliary information on extension versus time, also derived from the oscilloscope, complete stress strain curves were evolved at impact strain rates (10,000 min^{-1}). Specimens were machined from predetermined locations in the weld metal itself and in the heat affected zone. Specimens taken from the heat affected zone were correlated with the peak temperatures experienced at the various specimen locations. For comparison, specimens were also machined from samples of base material which had been subjected to various peak temperatures by furnace heat treatment.

D. Temperature Distributions

In order to correlate mechanical properties with peak temperature, distributions of peak temperature were established and confirmed by processes of calculation and measurement. The equation giving peak temperature as a function of distance from the weld is:[3]

$$\frac{1}{T_p - T_o} = 4.13 \rho C_p r' t \frac{V}{q} + \frac{1}{T_m - T_o} \qquad (1)$$

where

T_p = peak temperature experienced at a distance, r', from the edge of the weld zone in a plate of thickness, t.

T_o = initial temperature of plate.

V = velocity of arc.

q = heat flow rate from arc into plate.

ρ, C_p, T_m = density, specific heat, and melting point, respectively, of aluminum.

To use equation (1), knowledge of the efficiency with which heat is transferred from the arc to the plate is essential, because q is the net transfer to the plate, not the total volt-ampere product. In general, with the consumable electrode inert gas process, heat transfer efficiencies have been found greater than 90%. Combining this with the known thermal properties of aluminum yields:

$$\frac{1000}{T_p - T_o} = 1680\ t\ r\ \frac{V}{EI} + 0.82 \qquad (2)$$

where

E = arc voltage and

I = arc amperage.

and t, r, and V are expressed in inches and in./min.

Calculation of the peak temperature distribution was supplemented by measurement using temperature sensitive lacquers, and all results reported herein pertain to welds in which measured and calculated temperatures agree within 30°F.

E. Process and Testing Variables

(1) The variables included in the heat affected zone studies were peak temperature (produced either by heat treatment or welding), strain

rate (0.025, 2.5, and 10,000 min^{-1}), and, of course, the composition and initial degree of cold work in the material. Measurements were made of yield strength, tensile strength, elongation, and total energy absorbed in fracture.

(2) Fusion Zone

The variables in the fusion zone studies were, in addition to weld metal composition, the orientation of the test specimens (longitudinal and transverse), whether the specimen was machined from the first or second pass, and strain rate (0.025 and 10,000 min^{-1}). Again, determinations were made of tensile and yield strength, elongation, and energy absorbed in fracture.

III. Experimental Results

A. Correlation of Toughness with Strength and Elongation.

Using large transverse tensile specimen, at low rates of strain, it had been found in earlier studies that the total area under the stress strain curve was proportional to the product of maximum load (in pounds) and total elongation (in inches). This correlation is shown in Figure 2 and can be represented by the equation:

$$U = 0.88 \; PL \tag{3}$$

where

U = total energy absorbed (inch lbs)

L = total elongation

P = maximum load

It has been established this correlation holds also for the subsize tensile specimens taken from either the weld metal or any part of the heat affected zone, and at all rates of strain including impact. This simply means, regardless of composition and processing history, the shapes of stress-strain curves in aluminum-magnesium alloys exhibit very little variation.

The stress-strain curves obtained under impact conditions are derived from oscilloscopic traces, examples of which are presented in Figure 3. One significant detail is the appearance of a distinct yield point at impact strain rates, which is never observed in conventional tensile testing of these aluminum alloys.

B. Distribution of Mechanical Properties in the Weld Heat Affected Zone.

Heat affected zone data are presented in Tables III, IV, and V. Data are also included in these tables from specimens subjected to furnace excursions to various peak temperatures, and the tables are so arranged that direct observation can be made of the effect of strain rate, and the difference between the very high speed heat treatment imposed on material by welding and the vastly slower thermal cycle imposed by furnace heat treatment.

(1) 5356-H321

Whether by furnace heat treatment or the heat effect of welding, the higher the peak temperature, the lower are the yield and tensile strengths in the weld heat affected zone. It is difficult to define a specific softening or recrystallization temperature but close scrutiny of the data indicate, with furnace heat treatment, the softening effect is concentrated in the region 450-500°F, whereas in the heat affected zone of the weld a corresponding temperature is much higher, 700-800°F. Stated another way, at any given peak temperature the furnace treated specimen is substantially softer than the weld "heat treated" specimen. This reflects the time dependence of softening reactions, which shows up in strength measurements but is not evident in hardness measurements. Hardness as a function of peak temperature for 5356-H321 is shown in Figure 4 which represents both furnace and weld heat affected samples. Figure 4 led to the tentative conclusion that softening is an instantaneous reaction depending only on temperature and not on time, but the real meaning of Figure 4 in the light of Table III is that hardness and strength are not simply related in this material, and are differently influenced by excursions to elevated temperature. Increasing strain rate from 0.025 to 2.5 min^{-1} brings about a decrease in tensile strength, an increase in yield strength, and very little affect on ductility at all locations in the heat affected zone. Further increasing the strain rate up to impact brings about a slight reversal (decrease) in yield strength, a further decrease in tensile strength, and a substantial decrease (by a factor of 2 or 3) in elongation.

Upon comparing the properties at various locations in the heat affected zone with total transverse weld strengths reported earlier, it is found that when 5356-H321 is welded with matching filler, transverse tensile strength is lower than in any part of the heat affected zone and the strain is concentrated in the weld zone. Clearly, with matching chemistries, the weld metal is definitely softer than even that part of the heat affected zone which has experienced a peak temperature of 900°F, which should be high enough to bring about complete annealing.

(2) 5086-H112

With this material there is no distinct softening temperature, but rather a gradual decrease in strength starting at relatively low peak temperatures. In fact, the only alloy studied in this or earlier investigations which exhibited anything like a distinct softening temperature was 5356, and this is reflected in Figure 5 which shows, in terms of hardness, the response of various work hardening alloys to different maximum temperatures imposed by furnace heat treatment.

Here again, increasing the strain rate from 0.025 to 2.5 min^{-1} brings about a decrease in tensile strength and an increase in yield strength, with no important effect on ductility, as was the case with 5356. However, further increasing the rate of strain to impact levels brings about a further increase in yield strength and a restoration of tensile

strength to the level observed at 0.025 min^{-1}. The elongation is substantially reduced by increasing strain rate to impact level.

These results lend themselves to comparison with earlier work which involved welding 5086 - H112 with overmatching 5356 filler, and it is found that the ultimate transverse tensile strength of the weld is slightly less than at locations in the heat affected zone which experienced a peak temperature of 850°F. The indication is that even with overmatching filler, the annealed part of the heat affected zone is not necessarily strength limiting.

(3) 5083-F

Impact data were not collected with this material, and, as with the other two alloys, there was observed an increase in yield strength and a decrease in tensile strength with no important effect on elongation, upon increasing the strain rate from 0.025 to 2.5 min^{-1}. As was the case for 5086 there does not appear to be any distinct softening temperature.

C. Weld Metal Properties

The transverse strength and plasticity properties of welds, supplemented by the property distributions in weld heat-affected zones, described in the preceeding paragraphs and set forth in Tables III, IV, and V, clearly identify the weld zone itself as the region in which plastic strain tends to concentrate. For this reason it is the weld metal which determines strength, and is of critical importance to transverse ductility

and toughness. The major effort during the last 9 months of this program was directed to studies of weld metal properties and factors influencing these properties. The results are presented below in somewhat more exhaustive detail than in the section on heat affected zone studies, partly because it is felt the values may be of more documentary value and partly because the results are less predictable from the standpoint of classical physical metallurgy. Some fairly surprising patterns of behavior have been developed which may have more meaning in the future, when the state of knowledge of the structure and mechanical behavior of rapidly solidified alloys is more highly developed.[4,5]

All the work reported in the following paragraphs pertains to two-pass welds on 1/2 inch plate, one pass on each side. It had already been established from scrutiny of the transverse tensile test and hardness distributions reported earlier, that weld metal hardness and strength increased with increasing magnesium content and decreased with increasing arc energy input. The purpose of this last phase of the investigation has been primarily to obtain more exact information on the properties of weld metal at both low (0.025 min^{-1}) and impact (10,000 min^{-1}) rates of strain, and to determine the directionality of properties in weld metal, and the influence which the heat of a second pass in a deposit has on the properties of the first pass. In this sense, the properties described below all have been determined using test bars from complete welds, so that the first pass has experienced the heat influence of the subsequent pass, and the second pass is in the as-deposited condition, with no subsequent heat treatment of any kind.

The data for this phase of the investigation are summarized in Tables VI and VII.

(1) Slow Versus Impact Strain Rates

The effect of strain rate on weld metal properties can be gained from careful comparison of the values in Tables VI and VII, and are substantially the same as were observed for the weld heat-affected zone, reported in Tables III, IV, and V.

Ultimate Tensile Strength:

Slow strain tensile strength was always about 4-5000 psi higher than impact tensile strength.

	Range of Values	Average of all Values
slow strain	36,000 - 43,650	38,600
impact strain	30,167 - 37,700	33,900

Yield Strength:

Slow strain yield strength was always about 3-8,000 psi lower than impact yield strength.

	Range of Values	Average of all Values
slow strain	17,000 - 22,250	19,000
impact strain	18,917 - 29,250	23,100

Per Cent Elongation:

Slow strain elongation was always about 3 to 5 times greater than impact elongation.

	Range of Values	Average of all Values
slow strain	15.5 - 30.9	21.4
impact strain	2.8 - 7.5	5.25

Toughness:

Slow strain toughness was always about 4 or 5 times greater than impact toughness. This difference in toughness is attributable almost entirely to the corresponding difference in elongation.

	Range of Values	Average of all Values
slow strain	4,960 - 10,480	7,400
impact strain	785 - 2,198	1,500

Typical curves of stress versus strain demonstrating the effects above are shown in Figures 6 and 7.

(2) First Pass Versus Second Pass Properties

The effect of the second weld pass on the properties of the first are not perfectly clear cut, but the trends are of sufficient interest to be setforth in detail.

Ultimate Tensile Strength:

At low strain rate, there was no difference between the tensile strength of the first and second passes.

	Average of all Values
second pass	38,619
first pass	38,643

At impact strain rates, the tensile strength of the second pass was always slightly lower than that of the first pass, when testing was done in the longitudinal direction (parallel to the axis of the weld, perpendicular to the direction of principal heat flow during solidification, and therefore perpendicular to the axes of the columnar grains in the weld metal). When testing was done in the transverse direction, just the opposite was observed,

the tensile strength of the second pass was generally higher than that of the first pass.

Yield Strength:

At low strain rate the yield strength of the second pass was higher than that of the first pass (except for one combination, 5183 wire on 5456 plate).

Average of all Values

second pass	19,708
first pass	17,604

At impact strain rate, the situation was reversed, the yield strength of the second pass being lower than that of the first pass (again except for 5183 wire on 5456 plate).

Average of all Values

second pass	21,840
first pass	24,520

Per Cent Elongation:

At low rates of strain the elongation of the second pass was generally greater than that of the first pass, although the difference is not regarded as particularly significant.

Average of all Values

second pass	23
first pass	19

At impact strain rates, the elongation of the second pass was again generally slightly higher than that of the first pass.

Average of all Values	
second pass	5.3
first pass	4.4

Toughness:

At low strain rate, the toughness of the second pass was significantly greater than that of the first pass (except for 5183 filler on 5083 plate).

Average of all Values	
second pass	8,046
first pass	6,508

At impact strain rates, there was no significant difference in toughness between the first and second pass. Stress strain curves presented in Figure 8 show the reduction in ductility of the first pass, brought about by the heat of the second pass.

Hardness:

On the Rockwell B scale, the hardness of the second pass was always about 3 points lower than that of the first pass, for all alloy combinations tested.

(3) Transverse Versus Longitudinal Properties

The interplay among strain rate, weld metal chemistry, and directionality is rather involved, but the following trends are inescapable.

Ultimate Tensile Strength:

At low strain rate, no directionality was observed in the second pass, but in the first pass, the longitudinal tensile strength was greater than the transverse. At impact strain rates there was no directionality in the first pass, but in the second pass the transverse impact tensile strength was somewhat greater than the longitudinal.

Yield Strength:

There was no directionality observed in yield strength, except in the second pass at impact strain rate, where yield strength was greater in the transverse than in the longitudinal direction.

Per Cent Elongation and Toughness:

Elongation and toughness were generally greater in the longitudinal than in the transverse direction, where the transverse direction is considered to be perpendicular to the direction of welding.

(4) Summary

The second pass heat effects and the directionality observed in weld deposits strongly suggest that the metal solidifies partially as a supersaturated solid solution, which is subject to precipitation upon subsequent heating. The strength gain from this precipitation is more than offset by loss in ductility and toughness, leading to the recommendation that, wherever possible, 5,000 series alloys should be welded by single pass procedures.

IV. Conclusions

(1) The response of cold worked 5,000 series aluminum alloys to the heat of welding shows that softening is a time dependent phenomenon in terms of strength distributions, although this is not reflected in hardness distributions. Furnace heat treatment to a given peak temperature always results in a greater strength reduction than is brought about by rapid heating and cooling to and from the same peak temperature in the weld heat affected zone. The peak temperature which accomplishes a given degree of softening in a work hardened 5,000 series alloy is higher in the weld heat affected zone than it is under conditions of furnace heat treatment.

(2) In weld metal and in heat affected zones, generally the effect of increasing strain rate up to impact levels was to increase yield strength, decrease tensile strength, and markedly decrease elongation and toughness. There were some instances of reversal of the above trend in yield and tensile strengths, notably in 5356, but the influence of strain rate on the strength level was not large enough to be of great significance. One effect of interest was the observation of a distinct yield point at impact strain rates.

(3) Subsequent passes in 5,000 series aluminum alloy welds do not improve the properties of prior deposits. Elongation and toughness are higher in weld metal which has not been heat affected by subsequent passes.

(4) Elongation and toughness are directional in 5,000 series weld metal, being higher in the longitudinal than in the transverse direction.

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TABLE I

Chemical Composition of Plate and Filler Material

Alloy	Form	Mg (%)	Cr (%)	Mn (%)
		Nominal Composition		
5356	Filler Wire	4.5-5.5	0.05-0.20	0.05-0.20
5183	Filler Wire	4.3-5.2	0.05-0.15	0.50-1.0
5356	Plate	5.1	0.12	0.13
5086	Plate	4.0	0.10	0.45
5083	Plate	4.0-4.9	0.05-0.25	0.30-1.0
5456	Plate	4.7-5.5	0.05-0.20	0.50-1.0
		Actual Composition		
5356	Filler Wire	5.01		
5183	Filler Wire	--		
5356-H321	Plate	5.18		
5086-H112	Plate	4.19		
5083-F	Plate	--		
5456	Plate	--		

TABLE III

Heat Affected Zone Data

5356 - H-321 Base Stock: 5356 Filler

Temp. (°F)	Condition	0.025 in./in.-min. UTS (kpsi)	0.025 in./in.-min. Y.S. (kpsi)	0.025 in./in.-min. Elong. (%)	0.025 in./in.-min. Toughness in-lb/in^3	2.5 in./in.-min. UTS (kpsi)	2.5 in./in.-min. Y.S. (kpsi)	2.5 in./in.-min. Elong. (%)	2.5 in./in.-min. Toughness in-lb/in^3	Impact UTS (kpsi)	Impact Y.S. (kpsi)	Impact Elong. (%)	Impact Toughness in-lb/in^3
Base	Furnace	51.0	34.6	12.4	5440	---	----	---	----	--	---	---	---
Metal	Weld	----	----	----	----	---	----	---	----	--	---	---	---
200	Furnace	51.5	34.4	12.9	5720	49.6	39.2	12.6	5370	--	---	---	---
	Weld	----	----	---	----	----	----	----	-----	--	---	---	---
250	Furnace	50.7	34.4	12.4	5400	49.2	38.9	12.6	5330	--	---	---	---
	Weld	----	----	---	----	----	----	----	----	44.6	37.4	5.3	2030
260	Furnace	----	----	---	----	----	----	----	----	--	---	---	---
	Weld	----	----	---	----	----	----	----	----	47.1	38.2	5.4	2185
270	Furnace	----	----	---	----	----	----	----	----	--	---	---	---
	Weld	----	----	---	----	----	----	----	----	43.6	37.8	4.6	1725
300	Furnace	50.9	34.5	12.8	5600	49.3	38.2	12.6	5340	---	---	---	---
	Weld	----	----	---	----	----	----	----	----	---	---	---	---
310	Furnace	----	----	---	----	----	----	----	----	----	---	---	---
	Weld	----	----	---	----	----	----	----	----	45.6	37.7	3.9	1530
Below	Furnace	----	----	---	----	----	----	----	----	----	---	---	---
350	Weld	51.5	34.4	12.8	5660	51.1	38.2	13.5	5820	----	---	---	---
350	Furnace	---	----	---	----	49.2	38.6	12.2	5160	----	---	---	---
	Weld	51.5	34.7	12.4	5495	50.4	39.5	12.1	5210	----	---	---	---
380	Furnace	---	----	---	----	----	----	----	---	----	---	---	---
	Weld	---	----	---	----	----	----	----	---	44.5	37.3	4.2	1605

TABLE III (Continued)

Temp. (°F)	Condition	0.025 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³	2.5 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³	Impact UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³
395	Furnace	----	----	----	---	---	----	----	----	---	---	--	----
	Weld	----	----	----	---	---	----	----	----	44.8	37.6	5.6	2160
400	Furnace	50.6	34.4	11.8	5150	48.7	38.2	11.7	4900	---	----	--	----
	Weld	51.9	34.6	13.2	5885	50.2	39.1	13.2	5695	---	----	--	----
450	Furnace	50.3	33.1	12.2	5275	49.1	37.6	13.1	5530	---	----	--	----
	Weld	51.4	34.3	13.8	6100	49.8	38.2	13.6	5820	---	----	--	----
465	Furnace	----	----	----	----	----	----	----	----	---	----	--	----
	Weld	----	----	----	----	----	----	----	----	44.6	35.9	4.9	1880
500	Furnace	45.3	25.0	14.8	5760	41.1	27.4	19.2	6800	---	----	--	----
	Weld	50.5	33.5	13.6	5885	50.1	38.2	15.0	6460	---	----	--	----
565	Furnace	----	----	----	----	----	----	----	----	---	----	--	----
	Weld	----	----	----	----	----	----	----	----	44.6	35.9	4.9	1880
600	Furnace	----	----	----	----	41.8	23.6	23.2	8330	---	----	--	----
	Weld	50.6	32.7	14.1	6100	49.4	37.5	14.3	6070	---	----	--	----
630	Furnace	----	----	----	----	----	----	----	----	---	----	--	----
	Weld	----	----	----	----	----	----	----	----	44.6	35.0	5.2	1995
700	Furnace	43.2	19.1	23.5	8740	40.8	20.6	24.8	8700	---	----	--	----
	Weld	50.0	29.9	16.4	7020	33.8	47.8	15.7	6420	---	----	--	----
750	Furnace	----	----	----	----	----	----	----	----	---	----	--	----
	Weld	----	----	----	----	----	----	----	----	40.6	32.5	5.1	1780
800	Furnace	----	----	----	----	40.9	20.3	25.0	8800	---	----	--	----
	Weld	43.7	20.6	22.4	8410	41.9	23.6	24.1	8670	---	----	--	----
900	Furnace	42.3	18.6	26.4	9600	41.9	20.6	23.9	8250	---	----	--	----
	Weld	----	----	----	----	----	----	----	----	---	----	--	----

TABLE III (Continued)

Temp. (°F)	Condition	0.025 in./in.-min.				2.5 in./in.-min.				Impact			
		UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3
910	Furnace	----	----	---	----	---	----	--	----	---	----	--	----
	Weld	----	----	---	----	38.9	19.0	20.1	6710	40.8	24.3	6.4	2240

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UTS: Ultimate Tensile Strength (1000 psi)

Y.S.: Yield Strength (1000 psi)

Elong.: Percent Elongation in 0.8 inch.

Toughness: in.-lb./in.^{3} based on 0.8 inch gage length

TABLE IV

Heat Affected Zone Properties

5086 - H-112 Base Stock: 5356 Filler*

Temp. (°F)	Condition	0.025 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	2.5 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	Impact UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3
Base Metal	Furnace	40.5	24.2	17.8	6200	---	---	---	---	---	----	--	----
	Weld	---	---	---	---	---	---	----	---	---	----	--	----
200	Furnace	40.5	23.9	20.6	7170	38.2	26.8	14.4	4720	---	----	--	----
	Weld	---	---	---	---	---	---	----	---	---	----	--	----
210	Furnace	---	---	---	---	---	---	----	---	---	----	--	----
	Weld	---	---	---	---	---	---	----	---	39.4	28.4	6.3	2135
230	Furnace	---	---	---	---	---	---	----	---	---	----	--	----
	Weld	---	---	---	---	---	---	----	---	36.4	26.0	4.2	1315
250	Furnace	40.5	23.5	19.6	6825	37.4	26.8	14.4	4630	---	----	--	----
	Weld	---	---	---	---	---	----	----	---	40.7	28.0	4.5	1575
265	Furnace	---	---	---	---	---	----	----	---	---	----	--	----
	Weld	---	---	---	---	---	----	----	---	33.0	26.2	6.2	1760
290	Furnace	---	---	---	---	---	----	----	---	---	----	--	----
	Weld	---	---	---	---	---	----	----	---	40.5	28.5	4.8	1670
300	Furnace	40.6	23.2	20.0	6980	37.6	24.8	18.0	5820	---	----	--	----
	Weld	---	---	---	---	---	----	----	---	---	----	--	----
320	Furnace	---	---	---	---	---	----	----	---	---	----	--	----
	Weld	---	---	---	---	---	----	----	---	40.0	28.5	5.2	1790
350	Furnace	40.0	22.3	20.2	6950	37.3	24.8	15.7	5030	---	----	--	----
	Weld	---	---	---	---	----	----	----	---	37.8	27.2	4.4	1430

TABLE IV (continued)

Temp. (°F)	Condition	0.025 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	2.5 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	Impact UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in3
400	Furnace	40.0	21.8	21.5	7400	37.6	24.2	18.6	6170	---	---	----	----
	Weld	38.9	20.5	17.9	5960	38.5	26.2	18.4	6023	40.7	27.8	5.7	1995
440	Furnace	---	---	---	---	---	---	---	---	---	---	----	----
	Weld	41.0	21.0	20.6	7260	---	---	---	--	39.1	29.0	4.8	1615
450	Furnace	39.6	20.0	22.9	7800	37.2	22.9	18.1	5790	---	---	----	----
	Weld	40.4	20.7	20.2	7018	37.5	25.3	16.3	5238	---	---	----	----
480	Furnace	---	---	---	---	---	---	---	---	---	---	----	----
	Weld	---	---	---	---	---	---	---	---	39.2	26.7	5.2	1750
500	Furnace	39.0	18.8	---	---	36.9	21.7	18.8	5960	---	---	----	----
	Weld	39.7	20.1	20.2	6850	38.0	24.5	19.4	6308	---	---	----	----
550	Furnace	---	---	---	---	---	---	---	---	---	---	----	----
	Weld	39.5	18.8	21.9	7440	---	---	---	---	---	---	----	----
600	Furnace	39.0	18.4	21.4	7170	---	---	---	---	---	---	----	----
	Weld	38.8	19.5	17.6	5870	38.6	26.4	16.3	5410	---	---	----	----
625	Furnace	---	---	---	---	---	---	---	---	---	---	----	----
	Weld	40.0	19.5	19.3	6630	---	---	---	---	---	---	----	----
700	Furnace	39.0	17.5	22.1	7410	36.3	19.1	20.4	6370	---	---	----	----
	Weld	39.6	19.4	20.0	6810	36.9	23.3	17.6	5570	---	---	----	----
800	Furnace	39.0	15.9	24.5	8220	35.7	18.2	18.4	5650	---	---	----	----
	Weld	39.3	17.8	19.8	6690	37.9	23.2	19.5	6360	---	---	----	----
850	Furnace	---	---	----	---	---	---	---	---	---	---	----	----
	Weld	39.4	17.5	20.8	7040	---	---	---	---	---	---	----	----
900	Furnace	38.2	15.0	25.5	8380	36.0	18.5	24.7	7650	---	---	----	----
	Weld	---	---	---	---	---	---	---	---	---	---	----	----

TABLE IV (Continued)

Temp. (°F)	Condition	0.025 in./in-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³	2.5 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³	Impact UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in³
Fusion	Furnace	--	--	--	--	--	--	--	--	--	--	--	--
Zone	Weld	34.6	17.0	13.5	4015	32.2	20.5	13.4	3720	37.0	21.2	5.8	1845

* Impact specimens: 5183 Filler.

TABLE V

Heat Affected Zone Properties

5083-F Base Stock: 5356 Filler

Temp. (°F)	Condition	0.025 in./in.-min. UTS (kpsi)	0.025 Y.S. (kpsi)	0.025 Elong. (%)	0.025 Toughness in-lb/in^3	0.25 in./in.-min. UTS (kpsi)	0.25 Y.S. (kpsi)	0.25 Elong. (%)	0.25 Toughness in-lb/in^3	2.5 in./in.-min. UTS (kpsi)	2.5 Y.S. (kpsi)	2.5 Elong. (%)	2.5 Toughness in-lb/in^3
Base Metal	Furnace	45.2	34.6	11.8	4590	44.6	33.2	12.9	4950	---	---	---	---
	Weld	---	---	---	---	---	---	---	---	---	---	---	---
200	Furnace	45.0	32.2	12.9	4990	44.0	32.5	12.1	4580	42.7	37.8	11.1	4070
	Weld	---	---	---	---	---	---	---	---	---	---	---	---
250	Furnace	43.5	30.2	14.8	5530	43.7	30.6	15.0	5640	44.0	38.8	11.8	4460
	Weld	---	---	---	---	---	---	---	---	---	---	---	---
300	Furnace	---	---	---	---	42.9	28.7	14.2	5240	43.4	37.6	11.4	4260
	Weld	---	---	---	---	---	---	---	---	---	---	---	---
Below 350	Furnace	---	---	---	---	---	---	---	---	---	---	---	---
	Weld	47.5	34.7	12.4	5050	---	---	---	---	44.6	37.3	10.2	3910
350	Furnace	46.3	30.1	13.4	5340	43.0	26.8	17.4	6440	43.3	32.5	11.8	4390
	Weld	46.7	32.8	12.4	5020	---	---	---	---	45.7	37.3	12.1	4750
400	Furnace	45.6	28.5	13.4	5250	42.3	25.5	15.8	5750	42.0	31.9	16.7	6030
	Weld	46.2	31.2	12.9	5100	---	---	---	---	45.1	35.8	12.9	5000
450	Furnace	43.1	24.4	16.6	6150	42.3	24.4	19.4	7060	42.4	30.6	16.0	5840
	Weld	45.8	29.3	14.8	5800	---	---	---	---	44.6	34.9	11.5	4390
500	Furnace	---	---	---	---	42.0	22.9	19.8	7150	---	---	---	---
	Weld	44.2	26.1	15.5	5900	---	---	---	---	43.0	31.3	16.0	5850
600	Furnace	42.4	22.0	17.6	6410	41.5	21.9	21.5	7670	40.1	27.4	18.0	6200
	Weld	44.3	24.7	16.7	6350	---	---	---	---	42.5	29.2	17.3	6300
700	Furnace	41.7	20.7	19.1	6840	42.0	21.9	20.4	7360	40.1	25.5	20.2	6960
	Weld	43.6	23.3	17.2	6440	---	---	---	---	41.4	26.9	16.8	6070

Table V (Continued)

Temp. (^oF)	Condition	0.025 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	0.25 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3	2.5 in./in.-min. UTS (kpsi)	Y.S. (kpsi)	Elong. (%)	Toughness in-lb/in^3
800	Furnace	41.8	20.6	21.4	7690	---	---	---	---	40.7	22.9	22.0	7700
	Weld	44.3	22.6	18.8	7170	---	---	---	---	42.1	27.1	16.8	6080
900	Furnace	41.0	19.0	20.5	7230	---	---	---	---	---	---	---	---
	Weld	---	---	---	---	---	---	---	---	---	---	---	---
Fusion	Furnace	---	---	---	---	---	---	---	---	---	---	---	---
Zone	Weld	39.2	20.5	16.7	5610	---	---	---	---	35.2	21.6	16.8	5086

				Ultimate Tensile Strength	Yield Strength	Per Cent Elongation	Toughness
5183 WIRE	5083 PLATE	SINGLE PASS	TRANSVERSE	33,367	23,233	4·84	1,430
			LONGITUDINAL	33,100	19,917	6·94	2,031
		DOUBLE PASS	TRANSVERSE	36,850	25,000	3·57	1,152
			LONGITUDINAL	34,100	23,400	4·03	1,228
	5456 PLATE	SINGLE PASS	TRANSVERSE	37,700	24,250	5·36	1,618
			LONGITUDINAL	33,367	23,333	5·90	1,720
		DOUBLE PASS	TRANSVERSE	34,600	21,475	7·52*	2,113
			LONGITUDINAL	35,767	23,733	7·03	2,198
5356 WIRE	5083 PLATE	SINGLE PASS	TRANSVERSE	35,867	24,550	3·73	1,162
			LONGITUDINAL	32,867	21,250	6·57	1,897
		DOUBLE PASS	TRANSVERSE	32,850	24,875	3·74	1,167
			LONGITUDINAL	34,200	29,250	6·26	1,257
	5456 PLATE	SINGLE PASS	TRANSVERSE	33,400	23,167	3·83	1,127
			LONGITUDINAL	30,167	18,917	5·72	1,538
		DOUBLE PASS	TRANSVERSE	32,300	24,175	2·76	785
			LONGITUDINAL	32,900	20,417	5·92	1,600

Table VI. Impact Strain Tensile Data

				Ultimate Tensile Strength	Yield Strength	Per Cent Elongation	Toughness
5183 WIRE	5083 PLATE	SINGLE PASS	TRANSVERSE	39,700	22,250	19·2	6,910
			LONGITUDINAL	40,000	20,750	21·2	7,626
		DOUBLE PASS	TRANSVERSE	36,750	16,500	18·0	5,756
			LONGITUDINAL	39,500	20,125	26·1	9,324
	5456 PLATE	SINGLE PASS	TRANSVERSE	38,750	19,000	28·65	10,100
			LONGITUDINAL	40,375	20,000	24·3	8,716
		DOUBLE PASS	TRANSVERSE	40,375	21,500	21·8	8,320
			LONGITUDINAL	43,650	20,000	21·9	8,270
5356 WIRE	5083 PLATE	SINGLE PASS	TRANSVERSE	38,500	18,250	18·8	6,550
			LONGITUDINAL	37,875	19,250	30·9	10,480
		DOUBLE PASS	TRANSVERSE	37,750	17,000	18·55	6,270
			LONGITUDINAL	38,750	17,000	19·8	6,530
	5456 PLATE	SINGLE PASS	TRANSVERSE	37,750	18,750	17·8	5,980
			LONGITUDINAL	36,000	19,000	23·5	7,584
		DOUBLE PASS	TRANSVERSE	36,000	17,500	15·5	4,960
			LONGITUDINAL	36,375	17,500	17·3	5,450

Table VII. Slow Strain Tensile Data

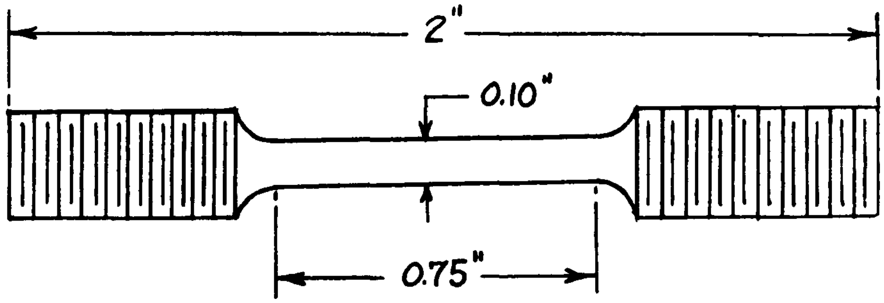


Figure 1

Test Bar

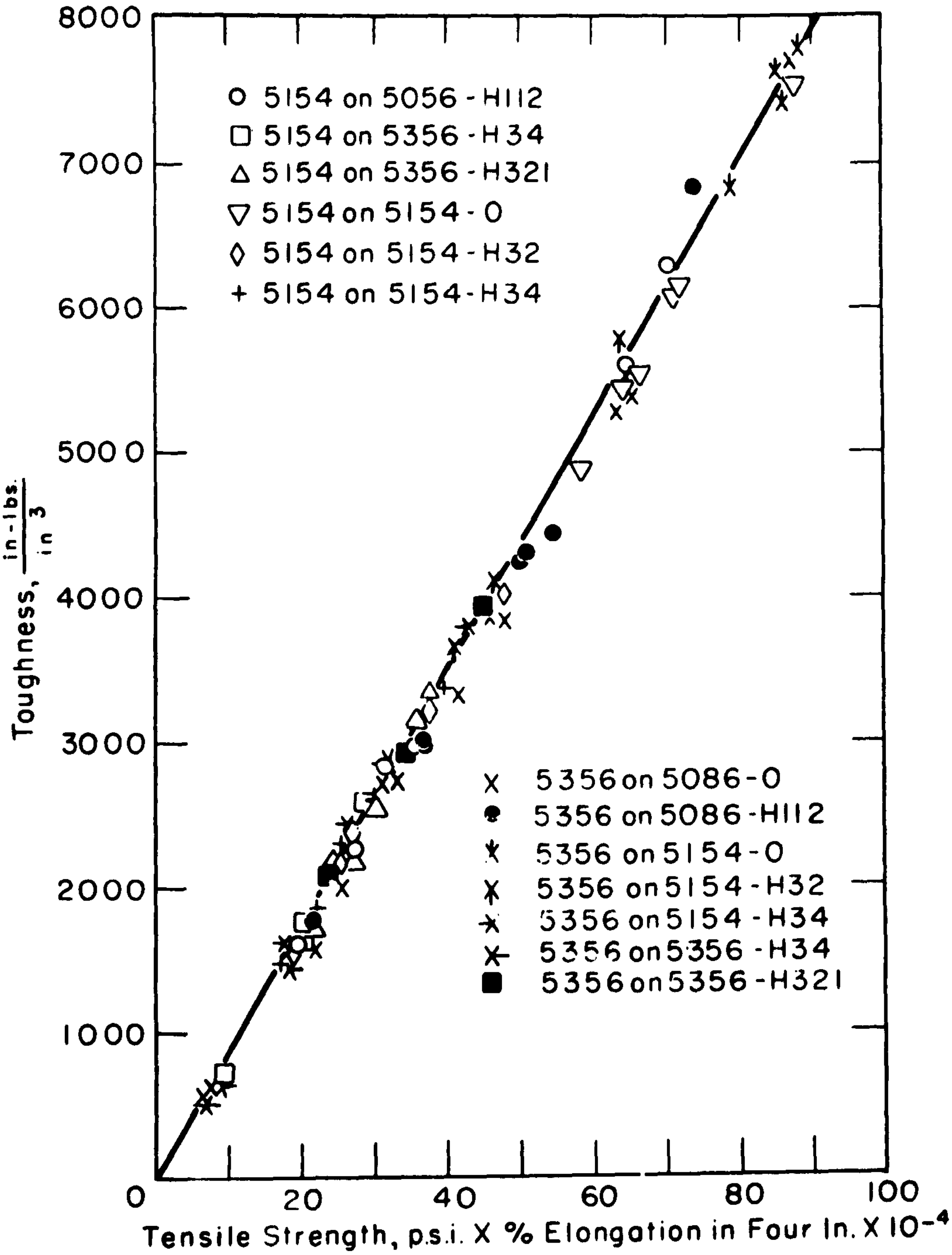
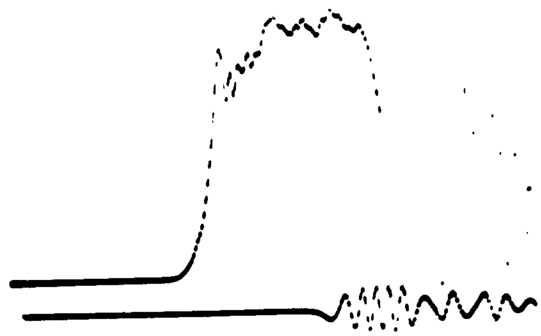
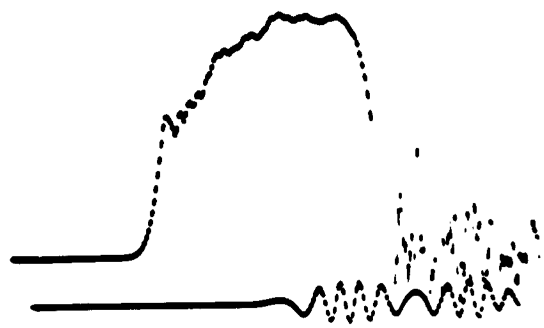


Figure 2 - Toughness Versus the Product of Ultimate Tensile Strength and Elongation in Four Inches



3a



3b

3c

Figure	Material	Peak Temperature	Ultimate Tensile Impact Strength	Elapsed Time
3a	5356-H321	250°F	44,500 psi	0.00065 sec.
3b	5356-H321	910°F	41,000 psi	0.00075 sec.
3c	5356	Fusion Zone	36,400 psi	0.00070 sec.

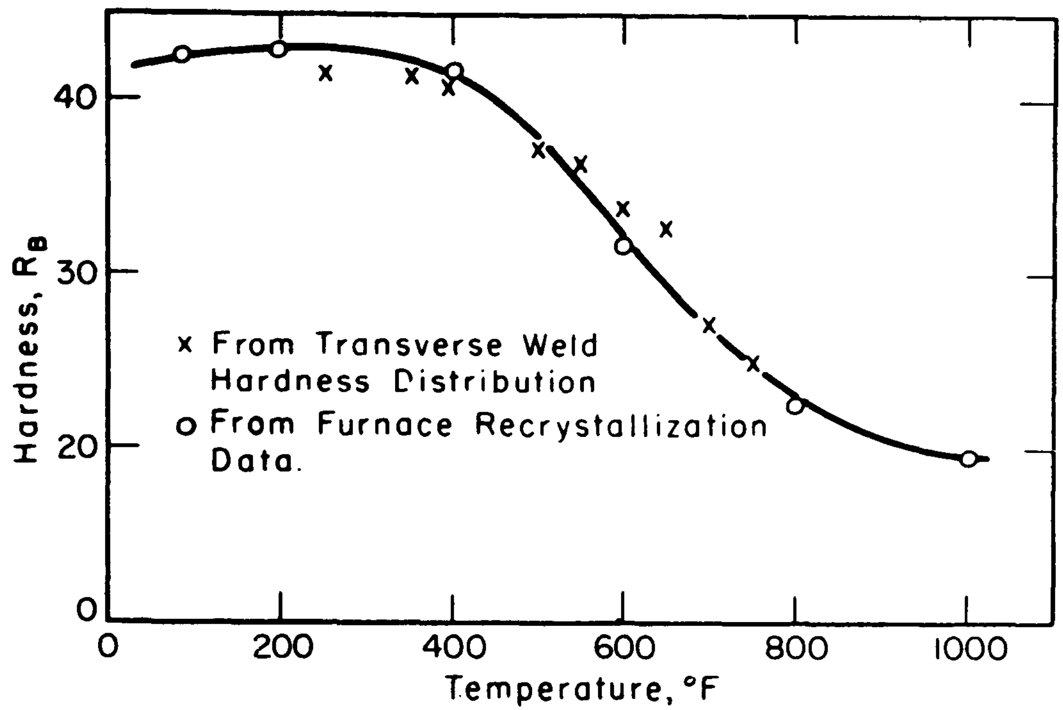


Figure 4 - Hardness as a Function of (a) Peak Temperature in Welding or (b) Furnace Annealing Temperature, Alloy 5356-H321

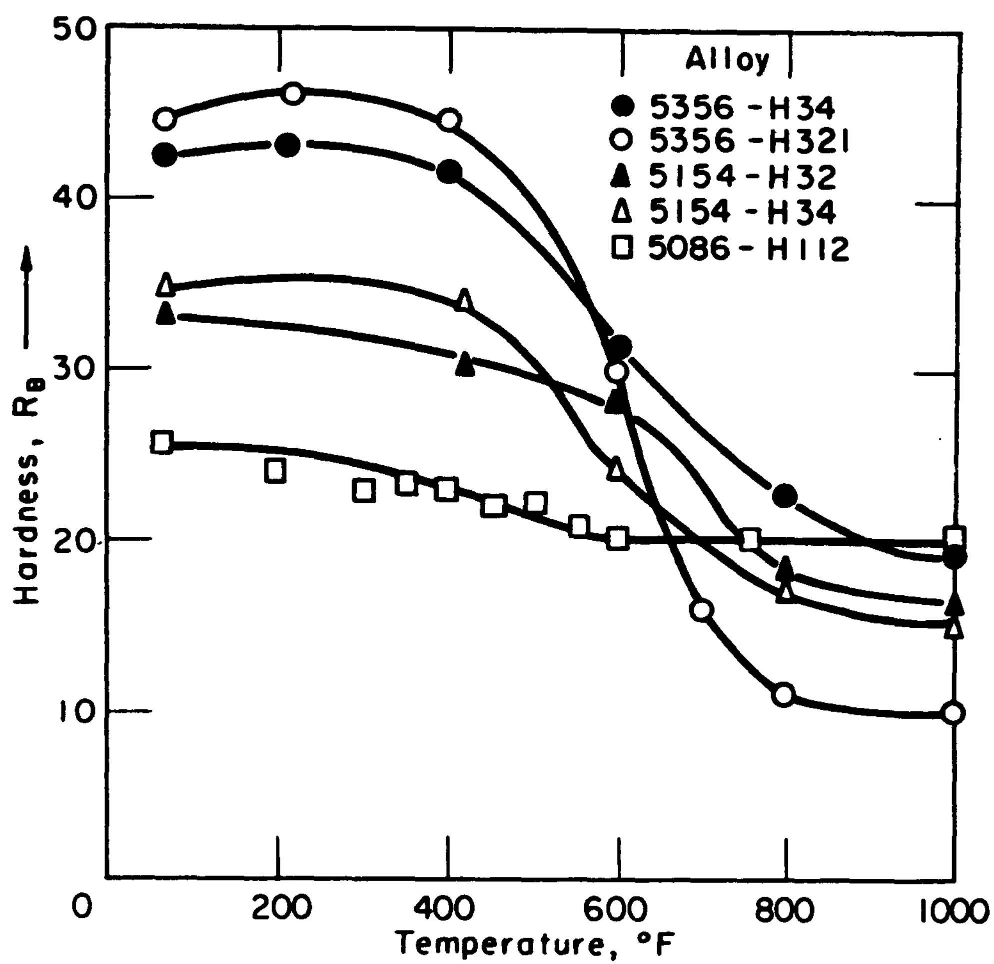


Figure 5 - Hardness Versus Furnace Annealing Temperature

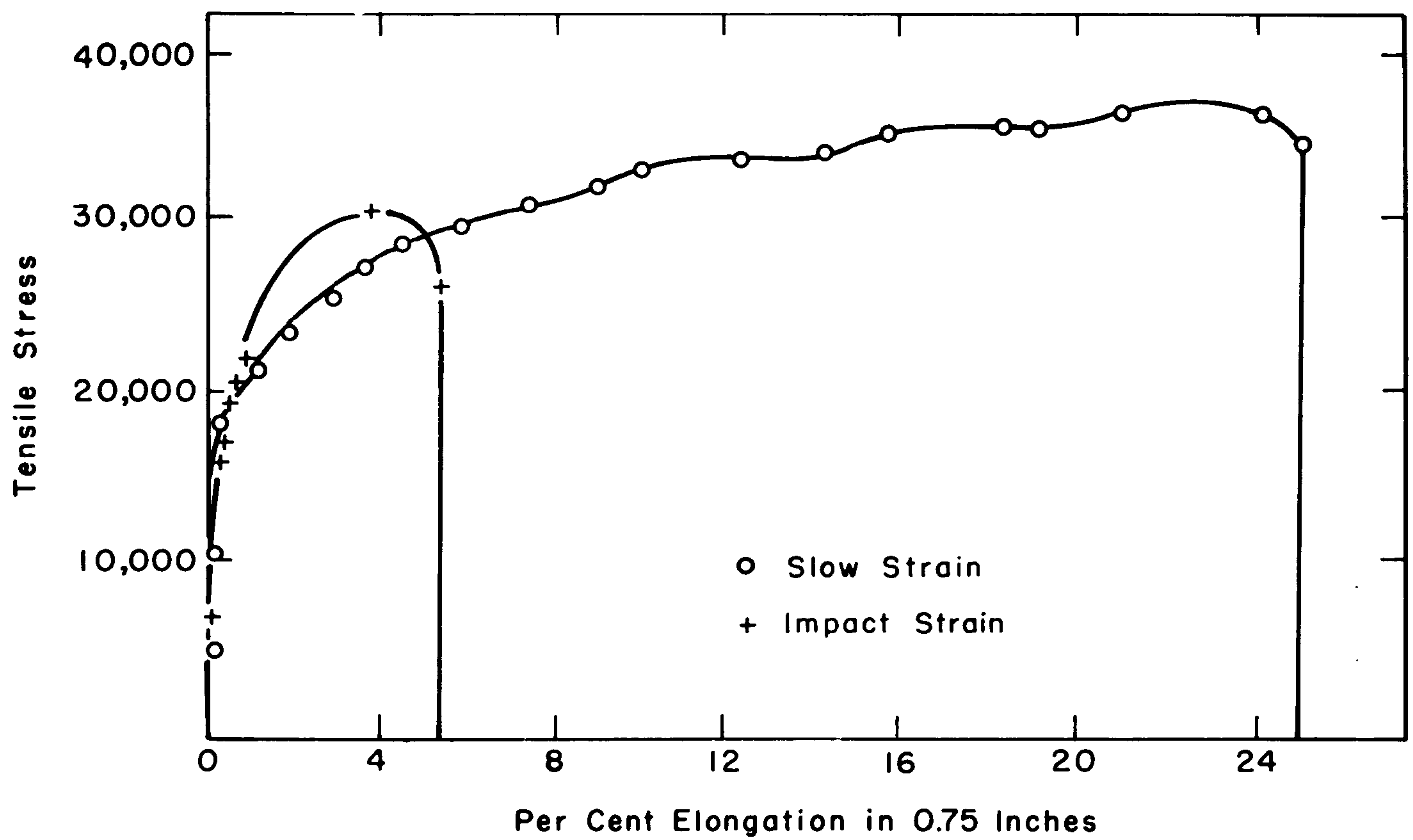


Figure 6. Stress Versus Strain for 5356 Wire on 5456 Plate, Second Pass, Longitudinal. Note the higher tensile strength and final elongation together with lower yield stress of the slow strain specimen as compared with the impact strain specimen.

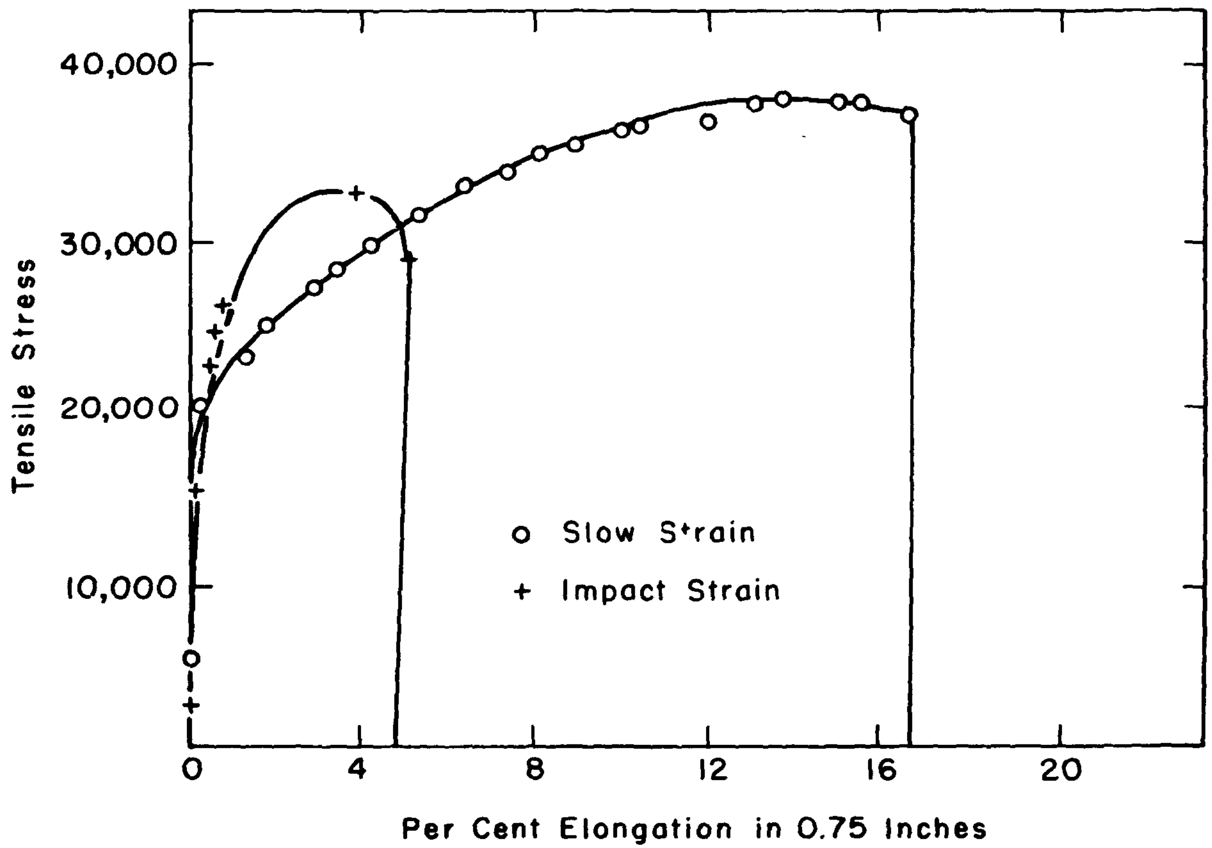


Figure 7. Stress Versus Strain for 5356 Wire on 5456 Plate, First Pass, Longitudinal. Note same characteristics as Figure 6. Influence of strain rate is seen to be independent of multiple pass effects.

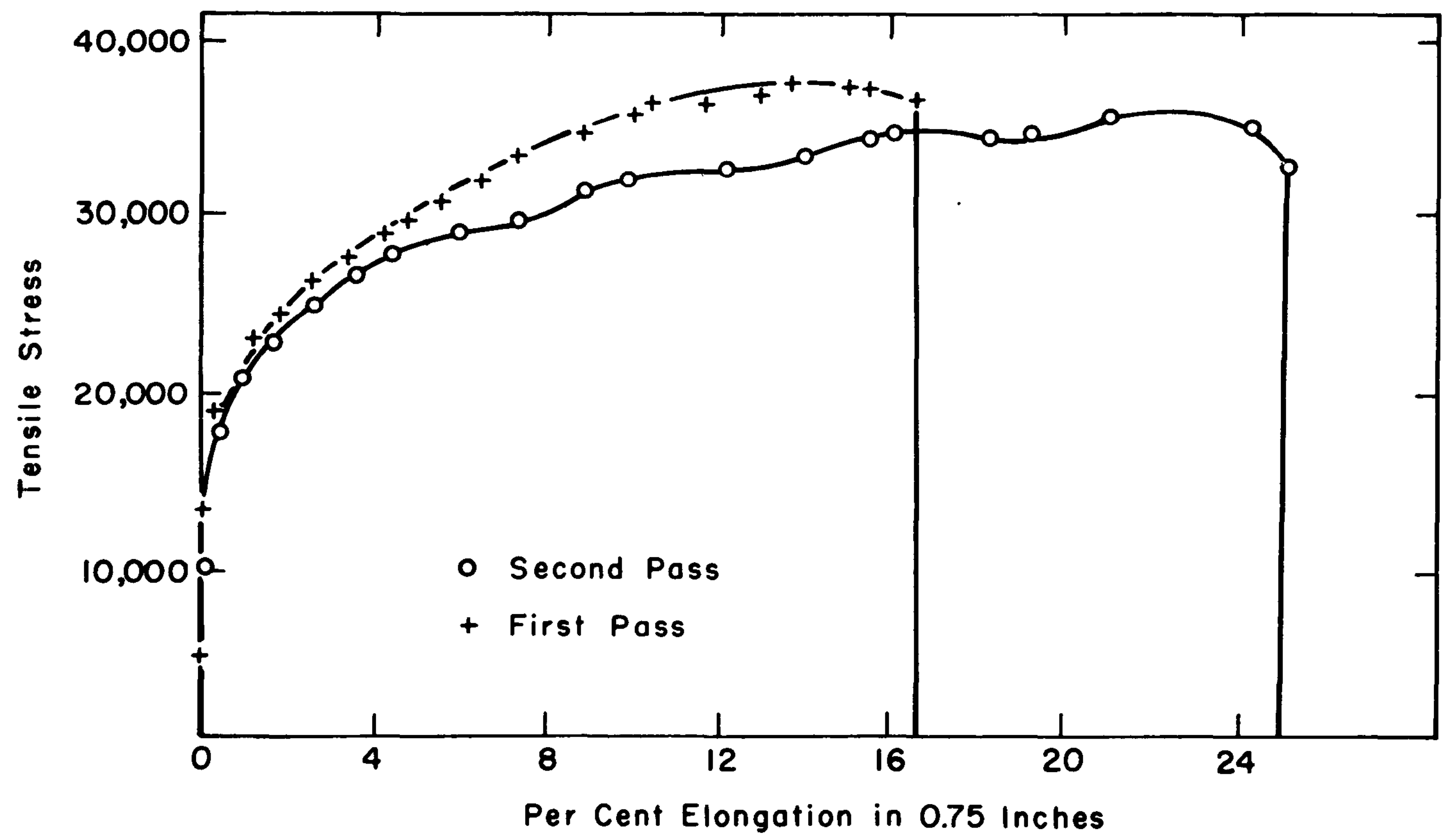


Figure 8. Stress Versus Strain for 5356 Wire on 5456 Plate, Slow Strain Rate, Longitudinal. This curve shows clearly the decreased elongation with second pass annealing.

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